

**Thursday, July 30, 1998**  
**EARLY CHRONOLOGY AND PLANETARY PROCESSES**  
**2:00 p.m. Ussher Theatre**

**Chairs: J. D. Gilmour**  
**G. Srinivasan**

Kita N. T.\* Nagahara H. Togashi S. Morishita Y.

*New Evidence of Aluminum-26 from an Ferrous-Oxide-rich Chondrule in Semarkona (LL3.0)*

Srinivasan G.\* Goswami J. N. Bhandari N.

*Search for Extinct Aluminum-26 in the Piplia Kalan Eucrite*

Pravdivtseva O. V.\* Hohenberg C. M. Brazzle R. H.

*Isotopic Record of Shock Metamorphism in the Richardton H5 Chondrite*

Hohenberg C. M.\* Brazzle R. H. Pravdivtseva O. V. Meshik A. P.

*Iodine-Xenon Chronometry: The Verdict*

Whitby J. A.\* Gilmour J. D. Turner G.

*In Situ Analysis of the Iodine-Xenon System in a Saharan EH3 Chondrite*

Burkland M. K.\* Swindle T. D.

*The Thermal Retentive Nature of the Iodine-Xenon System in the Ordinary Chondrite Bjurböle:  
Implications for the Iodine-Xenon System as a Chronometer of Early Solar System Events*

Kunz J.\* Allègre C. J.

*Terrestrial Xenology and Early Evolution of Earth*

Turner G.\* Burnard P. Harrison D.

*The Plane Truth About Primordial Noble Gases on Earth*

Ozima M.\* Podosek F. A.

*Formation Interval of the Earth from Iodine-129/Iodine-127 and Plutonium-244/Plutonium-238 Systematics  
and Missing Xenon*

Hohenberg C. M. Thonnard N.\* Kehm K. Meshik A. P. Berryhill A. Glenn A.

*Active Capture of Volatiles: Implication for Planetary and Atmospheric Xenon*

Manuel O.\*

*Isotopic Ratios in Jupiter Confirm Intrasolar Diffusion*

Hill L. C. Jr.\*

*The Urey Hypothesis Revisited: Molecular Genetics and Contemporary Chronologies*

**NEW EVIDENCE OF ALUMINUM-26 FROM A FEO-RICH CHONDRULE IN SEMARKONA (LL3.0).** N. T. Kita<sup>1</sup>, H. Nagahara<sup>2</sup>, S. Togashi<sup>1</sup>, and Y. Morishita<sup>1</sup>, <sup>1</sup>Geological Survey of Japan, 1-1-3 Higashi, Tsukuba 305-8567, Japan, <sup>2</sup>Geological Institute, University of Tokyo, Hongo, Tokyo 113-0033, Japan.

**Introduction:** The <sup>26</sup>Mg excess from the decay of <sup>26</sup>Al (half life = 0.73 Myr) were found from numbers of Al-rich chondrules in UOCs [1–3]. The initial <sup>26</sup>Al/<sup>27</sup>Al abundance of these chondrules ( $\sim 1 \times 10^{-5}$ ) are significantly lower than those of CAIs ( $\sim 5 \times 10^{-5}$ ), suggesting that the formation of chondrules took place at least 1–2 Myr after the CAIs formation. The Al-Mg age information was not available for the majority of chondrules in UOCs because they do not contain high (Al/Mg) phases for the Al-Mg study. The <sup>60</sup>Fe-<sup>60</sup>Ni system (half life = 1.5 Myr) will be an useful chronometer, though the estimates of the initial solar (<sup>60</sup>Fe/<sup>56</sup>Fe) ratios are uncertain in the range between  $10^{-6}$  and  $10^{-8}$  [4].

In this work we focused on Type-II POP chondrules from Semarkona (LL3.0) for <sup>26</sup>Al-<sup>26</sup>Mg and <sup>60</sup>Fe-<sup>60</sup>Ni study using SIMS. These chondrules contain FeO-rich olivine and pyroxene, set in a Si, Al, Fe -rich mesostasis with quenched crystals [5]. Therefore, they are suitable samples containing high Al/Mg and high Fe/Ni phases.

**Samples and Experiments:** A Type II chondrule “CH4” (0.5  $\times$  0.8 mm) was examined in a polished thin section of Semarkona (USMN 1805-9). The sample contains 100–300  $\mu$ m olivine phenocrysts (Fo = 88  $\sim$  83), which are normally zoned at the rim (Fo = 75). Pyroxene grains are smaller (30–100  $\mu$ m) and zoned (En = 77  $\sim$  83, Ws = 1  $\sim$  5). The composition of mesostasis is rich in Na, Al, and Si (65–70% SiO<sub>2</sub>, 4–8% Na<sub>2</sub>O, and 12–18 % Al<sub>2</sub>O<sub>3</sub>). The fibrous quench crystals with high Fe, Mg, and Ca (pyroxene ?) are abundant in the mesostasis. However, several areas larger than 5  $\mu$ m are free of quenched crystals and show Al/Mg ratios of as high as  $\sim$ 200 (EPMA data). These area were selected for the SIMS analyses. We used the Cameca IMS-1270 at the Geological Survey

of Japan for SIMS analyses [6]. The primary ion of O<sub>2</sub><sup>+</sup> was focused to a diameter of 3–6  $\mu$ m for Al-Mg analyses and 15  $\mu$ m for Fe-Ni analyses. The typical precision of single analyses was 3–7 ‰ for Mg isotopes and 5 ‰ for Ni isotopes.

**Results and Discussion:** The Al/Mg ratios of the mesostasis was as high as 160, and a clear <sup>26</sup>Mg excess was observed up to  $14 \pm 5$  ‰ (2 $\sigma$ ). The results from 6 data show a linear trend on the Al-Mg isochron diagram with the slope corresponding to (<sup>26</sup>Al/<sup>27</sup>Al) =  $(1.16 \pm 0.25) \times 10^{-5}$ . The result indicates that CH4 formed ( $1.56 \pm 0.23$ ) Myr after CAIs formation. The present Al-Mg results imply that Type-II chondrules formed contemporary with more refractory Al-rich chondrules. The <sup>56</sup>Fe/<sup>58</sup>Ni ratios of olivine were between 2300 and 2800. The mean value of 21 analyses ( $\delta^{60}\text{Ni} = -0.04 \pm 0.99$  ‰, 2 $\sigma$ ) do not show any detectable <sup>60</sup>Ni excess. The upper limit of <sup>60</sup>Fe/<sup>56</sup>Fe ratio in CH4 is calculated to be  $1.4 \times 10^{-7}$ . Using the Al-Mg relative age, the upper limit of the <sup>60</sup>Fe/<sup>56</sup>Fe ratio at the time of CAI formation is estimated to be  $3.3 \times 10^{-7}$ . This value is similar to the recent estimate of less than  $2 \times 10^{-7}$  using the FeS from an H4 chondrite with known U-Pb age [4].

**References:** [1] Srinivasan G. et al. (1996) *LPS XXVII*, 1257–1258. [2] Russell S. S. et al. (1996) *Science*, 273, 757–762. [3] Russell S. S. et al. (1997) *LPS XXVIII*, 1209–1210. [4] Shukolyukov A. and Lugmair G. W. *EPSL*, 119, 159–166. [5] Jones R. H. (1996) *GCA.*, 60, 3115–3138. [6] Kita N. T. et al. (1998) *Antarct. Meteorite Res.*, 11, 105–123

**SEARCH FOR EXTINCT ALUMINUM-26 IN PIPLIA KALAN EUCRITE.** G. Srinivasan, J. N. Goswami, and N. Bhandari, Earth Science and Solar System Division, Physical Research Laboratory, Ahmedabad 380 009, India (srini@prl.ernet.in).

The short-lived radionuclide  $^{26}\text{Al}$  (half-life  $\sim 0.7$  Ma) was postulated as a heat source for the early melting and differentiation of planetesimals by Urey in 1955 [1]. Since then the presence of  $^{26}\text{Mg}$  excess ( $^{26}\text{Mg}^*$ ) due to the decay of  $^{26}\text{Al}$  has been established in Ca-Al-rich Inclusions (CAIs) and chondrules [2-7]. The presence of extinct  $^{26}\text{Al}$  in Semarkona clast chondrule with initial  $^{26}\text{Al}/^{27}\text{Al} \sim 8 \times 10^{-6}$  suggests that  $^{26}\text{Al}$  abundance was sufficient to produce incipient melting of well insulated bodies of chondritic composition [7], although the relationship between basaltic achondrites and igneous clasts in chondrites is not clear. Several attempts over the last twenty five years to look for extinct  $^{26}\text{Al}$  in eucrites, angrites, mesosiderites [8-11], plagioclase-rich clast from North Haig ureilite [12], and "microgabbro" clast in Parnallee [13] have remained unsuccessful, although in several cases upper limits for  $^{26}\text{Al}$  abundance have been estimated. If the heat for melting of parent bodies of eucrites was generated from  $^{26}\text{Al}$  decay then some evidence for its presence must be seen in differentiated meteorites provided the parent bodies cooled on a time scale of few million years. The recently fallen eucrite Piplia Kalan [14] has been shown to be extremely old based on Sm-Nd and Pu-Xe ages [15,16]. We have measured Al-Mg composition in several plagioclase crystals from Piplia Kalan to further investigate the role of  $^{26}\text{Al}$  in early melting of parent bodies of differentiated meteorites.

One thin section (PK-97-1) was documented using a Cameca SX electron microprobe (NASA Johnson Space Center, Houston) and it exhibits both coarse grained and fine grained features. The major minerals are plagioclase ( $\text{An}_{95}$ ), Ca-rich and Fe-rich pyroxenes, and chromite and ilmenite are also present as minor phases. The coarser plagioclase grains are  $\sim 1\text{mm}$  in size and sometimes have tiny ( $10\text{--}100\ \mu\text{m}$ ) pyroxene grains within them. Coarse grained plagioclase and pyroxene crystals were studied for Al-Mg composition using Cameca ims-4F ion microprobe. Back scattered electron image of PK-97-1 was used to avoid pyroxene grains (hot spots of Mg) present within plagioclase crystals. The results of this study shows that  $^{27}\text{Al}/^{24}\text{Mg}$  value ranges from 3000-6000 in plagioclase with  $^{26}\text{Mg}^*$  values varying from 6‰ to 48‰. Our data yields initial ( $^{26}\text{Al}/^{27}\text{Al}$ ) value of  $(7.0 \pm 2.0) \times 10^{-7}$  ( $2\sigma_m$ ). This study provides for the first time a very strong evidence for the presence of live  $^{26}\text{Al}$  at the time of formation of eucrite Piplia Kalan and suggests a time interval of  $\sim 5$  Ma between the formation of CAIs and this meteorite. The contribution of cosmogenic  $^{26}\text{Al}$  in this meteorite with an exposure age of 23 Ma [16] is  $<0.1\%$  of the measured excess. Our results confirm the antiquity of this meteorite as indicated by the Sm-Nd ages and suggest that  $^{26}\text{Al}$  could have played an important role as a heat source in the formation of differentiated meteorites.

References: [1] Urey H. (1955) *Proc. Natl. Acad. Sci. US*, 41, 127. [2] Lee T et al. (1976) *Geophys. Res. Lett.*, 3, 109. [3] MacPherson G. J. et al. (1995) *Meteoritics*, 30, 365. [4] Srinivasan G. et al. (1996) *LPSC XXVII*, 1257. [5] Srinivasan G. et al. (1996) *Meteoritics and Planet. Sci.*, 31, A133 [6] Russell S. S. et al. (1996) *Science*, 273, 757. 4571. [7] Hutcheon I. D. and Hutchison R. (1989) *Nature*, 337, 238. [8] Schramm D. et al. (1970) *EPSL*, 10, 44. [9] Bernius et al. (1991) *LPSC XXII*, 93. [10] Lugmair G. W. and Galer S. J. G. (1992) *GCA*, 56, 1673. [11] Hsu W. and Crozaz G. (1996) *GCA*, 60. [12] Davis A. et al. (1988) *LPSC XIX*, 251. [13] Kennedy A. et al. (1992) *EPSL*, 113, 191. [14] Shukla A. et al. (1997) *Meteoritics and Planet. Sci.*, 32, 611. [15] Kumar A et al. (1997) Conf. Isotopes in the Solar System (PRL, Ahmedabad) 11. [16] Bhandari N. et al. (1997) *Meteoritics and Planet. Sci.*, in press.

**ISOTOPIC RECORD OF SHOCK METAMORPHISM IN THE RICHARDTON H5 CHONDRITE.** O. V. Pravdivtseva, C. M. Hohenberg, and R. H. Brazzle, Department of Physics, Washington University, St. Louis MO 63130, USA (am@howdy.wustl.edu).

**Introduction:** Shock metamorphism and brecciation are common features in meteorites. Impact processes in general affect fundamental properties of meteorites, such as the abundance and distribution of noble gases and trace elements (particularly volatile elements), the radiometric ages, and other physical characteristics. The I-Xe isotopic system provides the ability to recognize and study fundamental processes such as shock metamorphism which took place in the early history of the meteorite parent bodies.

**Results:** Iodine-xenon measurements have recently been completed on 5 mineral separates from the H5 Richardton chondrite. In spite of Richardton's high petrological type, it shows a low degree of chondrule-matrix integration [1]. X-ray studies of Richardton olivine suggest that this meteorite has been mildly shocked, but has experienced little reheating since 4.5-4.6 Ga ago [2, 3]. The Pb-Pb age for Richardton phosphate was determined to be  $4.5534 \pm 0.0006$  [4].

Measured I-Xe ages for different Richardton mineral separates are shown in the table referenced to Shallowater's inferred Pb-Pb age of  $4.566 \pm 0.002$  Ga [5]. Total iodine content is shown in the third column, and iodine correlated with  $^{129}\text{Xe}$  is indicated in parenthesis [5].

Mineral	I-Xe age, Ma (after Shallowater)	I, ppb
Chromium spinel	$0 \pm 2$	4.0 (0.1)
Pyroxene	$-1.1 \pm 2$	20 (10)
Feldspar	$8.2 \pm 0.5$	119 (60)
Troilite	$10 \pm 2$	0.21 (0.07)
Apatite	not defined [5]	2.3 (–)

The I-Xe ages of Cr-spinel and pyroxene are the same as the Shallowater reference meteorite. Feldspar and troilite indicate Xe closure about 10 Ma after primary mineralization, presumably from shock resetting of the I-Xe clock. I-Xe ages of feldspar and troilite show good agreement, while the concentration of correlated iodine in troilite is three orders of magnitude lower. The differences in iodine concentrations among minerals could reflect their ability to capture volatiles and retain them during subsequent metamorphic events. Indeed, the I-Xe isotopic system of more refractory chromium spinel and pyroxene phases survived shock metamorphism. The concentration of iodine is highest in feldspar. Since only 50% of the Xe released from feldspar during stepwise heating is correlated with radiogenic  $^{129}\text{Xe}$  (1500–1800°C), a significant amount of iodine-derived  $^{129}\text{Xe}$  must have been lost after the high temperature iodine and Xe sites closed. Only 33% of the iodine is correlated in troilite, possible reflecting shock heating and melting. This result agrees with observations of shock heating and partial melting effects for different types of minerals in Richardton [3].

The I-Xe isotopic system of apatite was completely disturbed [5]. Although the concentration of iodine in apatite was 2.3 ppb, no correlated iodine was found.

**Acknowledgments:** This work was supported by NASA grant NAG5-4173.

**References:** [1] Evensen et al. (1979) *EPSL*, 42, 223–236. [2] Taylor G. J. and Heymann D. (1969) *EPSL*, 7, 151–161. [3] Stöffler et al. (1991) *GCA*, 55, 3845–3867. [4] Göpel C. et al. (1994) *EPSL*, 121, 153–171. [5] Brazzle R. H. et al. (1998) *GCA*, submitted.

**IODINE-XENON CHRONOMETRY: THE VERDICT.** C. M. Hohenberg, R. H. Brazzle, O. V. Pravdivtseva, and A. P. Meshik, Department of Physics and McDonnell Center for Space Sciences, Washington University, St. Louis MO 63130, USA (cmh@wuphys.wustl.edu).

The I-Xe system has long been questioned as a chronometer [1]. Its potential precision and unique abilities put us on a six year journey to test the I-Xe against the the Pb-Pb clock on single mineral systems [2,3]. New work, presented here, show that the I-Xe and Pb-Pb clocks are concordant in 11 different phosphate and feldspar separates. There are no discordant ages on the same mineral phase. The I-Xe clock generally records post-formational processing, since most iodine hosts are secondary minerals, providing a record of early meteorite evolution. Absolute I-Xe ages can now be found by normalization through the measured I-Xe and Pb-Pb ages of Acapulco phosphate ( $4.557 \pm .002$  Ga), leading to absolute ages for the I-Xe internal standards Shallowater and Bjurböle,  $4.5658 \pm .002$  Ga and  $4.565 \pm .003$  Ga, respectively. Allegan feldspar has among the oldest of absolute of I-Xe ages, equal to that of Murchison and Orgueil magnetite, presumably primary minerals, whereas phosphate and most feldspar reported here are secondary. The time of aqueous alteration on the CV parent body is  $4 \pm 2$  Ma after CAI formation, determined from the absolute I-Xe age of CAI sodalite. Pre-compaction irradiation of individual olivines in Murchison and Murray require a regolith residence time of at least 300 Ma for contemporary (GCR and SCR) energetic particles [4,5]. If termination of free regolith activity by aggregation is associated with aqueous alteration, as suggested by the carbonate and sulfate features in CI and CM meteorites, there is insufficient time. The large pre-compaction effects observed, require a much more intense source of energetic particles, at least two orders of magnitude higher than present solar flares, an early active (T-Tauri) sun.

**Acknowledgements:** This work was supported by NASA grant NAG5-4173.

**References:** [1] Swindle T. D. and Podosek F. A. (1988) *Meteorites in the Early Solar System*, Univ. Ariz. Press, 1127–1146. [2] Brazzle R. N. et al. (1998) *GCA*, submitted. [3] Nichols R. H. et al. (1994) *GCA*, 58, 2553–2561. [4] Caffee M. W. et al. (1987) *Astrophys. J.*, 313, L31–L35. [5] Woolum D. S. and Hohenberg C. M. (1993) *Protostars and Planets III*, Univ. Ariz. Press, 903–919.

Sample	Absolute I-Xe ages, Ga	Pb-Pb ages, Ga
Shallowater, irradiation monitor	$4.566 \pm .002$	–
Phosphate Separates		
H4 Beaver Creek	$4.569 \pm .005$	–
H4 Phum Sambo	–	–
H4 St. Marguerite	$4.567 \pm .006$	$4.5630 \pm .0006$
H5 Allegan	–	$4.5563 \pm .0008$
H5 Richardton	Disturbed	$4.5534 \pm .0006$
H6 Guarena	–	$4.5056 \pm .0005$
H6 Kernouve	$4.534 \pm .007$	$4.5214 \pm .0005$
L6 Modoc	$4.509 \pm .004$	–
L6 Walters	$4.512 \pm .004$	–
LL6 St. Severin	–	$4.5571 \pm .0015$
Acapulco	$\equiv 4.557 \pm .002$	$4.557 \pm .002$
Feldspar Separates		
H4 Phum Sambo	$4.567 \pm .002$	–
H4 St. Marguerite	$4.567 \pm .002$	–
H5 Allegan	$4.573 \pm .003$	–
H5 Richardton	$4.558 \pm .002$	–
LL6 St. Severin	$4.558 \pm .004$	–
Acapulco	$4.562 \pm .003$	–
Allende CAIs (sodalite, iodine host)		
USNM #3529-40	$4.563 \pm .002$	–
USNM #3529-43	$4.563 \pm .002$	–
USNM #3598	$4.562 \pm .002$	–
USNM #3803	–	–

**Introduction:** Unequilibrated enstatite chondrites seem not to have undergone the aqueous alteration processes that have affected most unequilibrated ordinary chondrites, and so may have preserved an unambiguous chronology for the formation of the objects within them (chondrules and matrix minerals) [1]. Previous work has demonstrated that the I-Xe chronometer can be successfully applied to this class of meteorites [2,3] despite the resetting of the  $^{40}\text{Ar}$ - $^{39}\text{Ar}$  system, and encouraged us to attempt the *in situ* analysis of the xenon isotopic system within a recently recovered EH3 from the Sahara. Sahara 97096 (one of several paired masses) has been described as a highly primitive EH3 chondrite which has retained primary accretional nebular features [4] in the form of sulfide-metal-rich chondrules. Our sample is from one of the other masses, but appears similar in all respects.

**Method:** Two polished blocks 5mm square and 500 $\mu\text{m}$  thick were prepared from a chip (avoiding the use of any aqueous media in the polishing stages) and back-scattered electron images of the sections were obtained. Selected phases were analyzed semi-quantitatively with an electron microprobe to aid interpretation of the back-scattered image. After neutron irradiation (batch MN11) one of the sections was loaded in the RELAX mass spectrometer [5] and a Q-switched Nd:YAG laser used to probe selected spots. Initial investigation has concentrated on a silicate chondrule of circular cross-section (diameter 1mm) bisected by one edge of the section.

**Results:** The figure summarises data from eighteen points obtained in a traverse across the diameter of the chondrule. The spot size is 70 $\mu\text{m}$  and spot centres are about 80 $\mu\text{m}$  apart. As expected,  $^{129}\text{Xe}^*/^{128}\text{Xe}^*$  ratios exhibit a plateau in the centre of the traverse, reflecting the formation age of the chondrule (standards for this irradiation have not yet been analysed). This pattern is disturbed at the edges where a contribution is made by matrix material around the rim of the chondrule generally resulting in lower  $^{129}\text{Xe}^*/^{128}\text{Xe}^*$  values (later apparent ages). The concentration of the trapped planetary component can be seen to increase dramatically outside the chondrule, as expected for the fine-grained matrix.

The utility of *in situ* I-Xe dating having been demonstrated, we will report formation ages and iodine concentrations of chondrules and matrix minerals within this unequilibrated EH3 meteorite and discuss

the implications of our results for the formation of the enstatite chondrites.

**References:** [1] El Goresy A. (1988) *Proc. NIPR Symp. Antarct. Meteorites 1*, 65–101. [2] Kennedy B. M. et al. (1988) *GCA*, 52, 101–111. [3] Ash R. D. et al. (1997) *LPSC XXVIII*. [4] Weisberg M. K. and Prinz M. (1998) *LPSC XXIX*. [5] Gilmour J. D. et al. (1994) *Rev. Sci. Instrum.*, 65, 617–625.

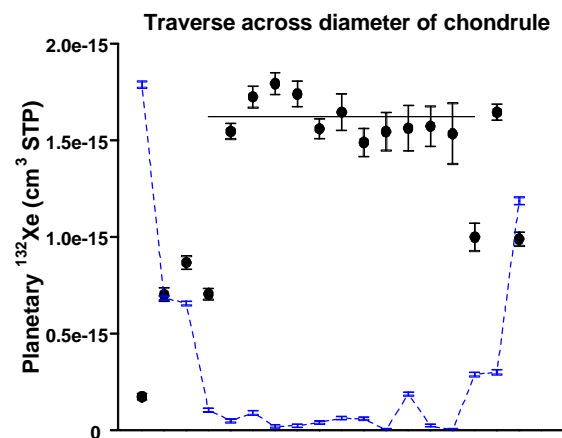


Figure shows laser probe data across a 1mm diameter chondrule. Solid symbols are ratios of iodine derived  $^{129}\text{Xe}$  to  $^{128}\text{Xe}$ , other points are amounts of  $^{132}\text{Xe}$  associated with planetary gas. The horizontal line shows the weighted mean of the central eleven points to be 0.947; error bars shown represent one standard deviation.

**THE THERMAL RETENTIVE NATURE OF THE I-Xe SYSTEM IN THE ORDINARY CHONDRITE BJURBÖLE: IMPLICATIONS FOR THE IODINE-XENON SYSTEM AS A CHRONOMETER OF EARLY SOLAR SYSTEM EVENTS.** M. K. Burkland and T. D. Swindle, Lunar and Planetary Laboratory, University of Arizona, Tucson AZ 85721 USA (burkland@lpl.arizona.edu).

To understand the response of the I-Xe system to thermal alteration, isothermal heating experiments were performed on the Bjurböle (L4) standard used for I-Xe dating. The time dependence of the release of radiogenic  $^{129}\text{Xe}$  and  $^{127}\text{I}$  was determined by analyzing Bjurböle heated for various times at temperatures of 1000°, 1100°, and 1200°C using noble gas mass spectrometry. Microprobe analyses on thin sections of heated Bjurböle were done to correlate chemical, mineralogical, and textural alterations with Xe and I release in hope of constraining the identity of the host phase of I.

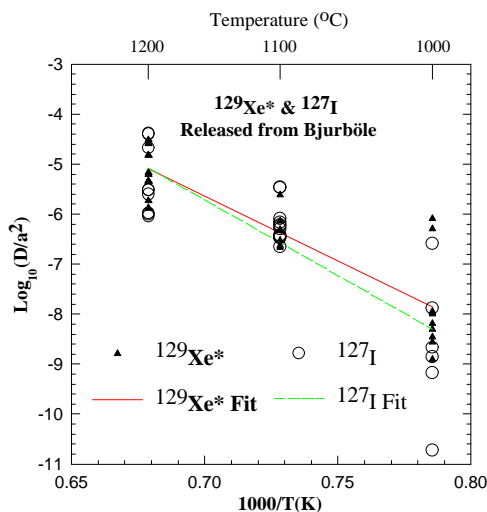
Results for the release of radiogenic  $^{129}\text{Xe}$  indicate that a single domain (site of radiogenic  $^{129}\text{Xe}$ ) model is insufficient to describe the release[1]. At least three, and possibly more, domains are present in Bjurböle. At least one domain outgasses in one hour at a temperature  $\leq 1000^\circ\text{C}$  by a mechanism that is not indicative of volume diffusion. For the 1100°C heating, one domain containing the majority of radiogenic  $^{129}\text{Xe}$  in Bjurböle is seen to outgas in a manner suggestive of volume diffusion. Release characteristics at 1200°C indicate the presence of at least one high temperature domain. The release of  $^{127}\text{I}$  is similar to that of radiogenic  $^{129}\text{Xe}$  for the three isothermal heating temperatures.

In domains that contain I-correlated Xe, assuming loss by volume diffusion, Dodson closure temperatures[2] for radiogenic  $^{129}\text{Xe}$  (along with more retentive  $^{127}\text{I}$ ) are at least as high, and perhaps much higher than, the peak metamorphic temperature experienced by Bjurböle. The resultant Dodson closure temperature for  $^{129}\text{Xe}^*$  is 649°C and for  $^{127}\text{I}$  is 677°C (see figure of Arrhenius plot). Taking into account the contribution of the low temperature domain raises the Dodson closure temperatures to 826°C and 879°C for  $^{129}\text{Xe}^*$  and  $^{127}\text{I}$ , respectively, well above the peak temperature range for grade 4 metamorphism.

Based on diffusion parameters, the diffusion lengths of both radiogenic  $^{129}\text{Xe}$  and  $^{127}\text{I}$ , at peak metamorphic temperatures, are much less than a characteristic domain size of  $10^{-3}\text{cm}$ , 0.4 to 1.0  $\mu\text{m}$  and 0.1  $\mu\text{m}$ , respectively. The

data suggest that the degree of thermal retention of both isotopes is great enough under thermal metamorphic conditions that the initial iodine ratio was not altered.

While the physical identities of the host phases in Bjurböle are not discernible from this experiment, the data does suggest the I-Xe system in Bjurböle is unaltered by thermal metamorphism experienced in the L-chondrite parent body. Therefore, if the release of radiogenic  $^{129}\text{Xe}$  is governed by volume diffusion, the I-Xe system is likely dating pre-metamorphic events.



Arrhenius plot of the release of  $^{129}\text{Xe}^*$  and  $^{127}\text{I}$  from isothermal heating. The slope is proportional to the activation energy, yielding the high Dodson closure temperatures reported.

**References:** [1] Burkland M. K., Swindle T. D., and Baldwin S. L. (1995) *GCA*, 59, 2085–2094. [2] Dodson M. H. (1973) *Contr.Mineral. and Petrol*, 40, 259–274.

**TERRESTRIAL XENOLOGY AND EARLY EVOLUTION OF EARTH.** J. Kunz and C. J. Allègre, Institut de Physique du Globe de Paris, Laboratoire de Géochimie et Cosmochimie, 4 place Jussieu, 75252 Paris Cedex 05, France (kunz@ipgp.jussieu.fr).

Recent contributions to rare gas systematics in Earth's mantle have significantly improved the existing constraints about fundamental processes like accretion and degassing of our planet. A close correlation of neon excesses with argon and xenon excesses in upper mantle derivatives (Mid-Oceanic Ridge Basalt glasses) is observed [1]. Using an upper limit of 13.8 (=solar) for mantle  $^{20}\text{Ne}/^{22}\text{Ne}$  a reliable upper limit of 8.2 can be given for mantle  $^{129}\text{Xe}/^{130}\text{Xe}$  excesses [1]. The only commonly accepted source of these excesses is  $^{129}\text{I}$  ( $T_{1/2} = 16$  Ma), which was still alive when Earth's mantle started to retain xenon isotopes.  $^{129}\text{Xe}$  excesses previously found in MORBs have established a timescale of less than 150 Ma for accretion and degassing of our planet [2,3]. This chronology can be refined by other isotopic systems like Pb-Pb [3] or  $^{182}\text{Hf}$ - $^{182}\text{W}$  [4], [5].

New Xe analyses of MORB glasses [6] give evidence that short-lived  $^{244}\text{Pu}$  ( $T_{1/2} = 80$  Ma) also contributed to the Xe budget of Earth's mantle. These analyses indicate that  $32 \pm 10\%$  ( $2\sigma$ ) of fissionogenic  $^{136}\text{Xe}/^{130}\text{Xe}$  excesses relative to present atmospheric composition were produced by spontaneous fission of plutonium. The remainder results from spontaneous fission of  $^{238}\text{U}$ . This result solves the conflicting findings for other mantle derivatives:  $\text{CO}_2$  well gas data indicate no plutoniogenic contribution [7], while data on mantle diamonds seem to exclude any uranogenic fission xenon in the mantle [8]. However, these two mantle derivatives appear to be less pristine samples of Earth's interior compared to MORBs, i.e. they most likely contain some additional  $^{238}\text{U}$  derived fission xenon [6].

In order to address the criticism that [6] have calibrated the fission Xe excesses only versus air standards we have measured some crustal samples also showing fission xenon excesses. We find, as expected, a pure uranogenic composition of the fission Xe. Thus, we proved to be sensible for some addition of plutoniogenic Xe isotopes.

The  $^{244}\text{Pu}$ - $^{136}\text{Xe}$  chronometer can be combined with the refined constraints on the  $^{129}\text{I}$ - $^{129}\text{Xe}$  system of Earth. Using reasonable parameters for solar system initial isotopic and elementary ratios of I, U, and Pu, one can calculate that no more than  $\sim 80$  Ma had passed between first retention of xenon isotope in primitive meteorites and the beginning of accumulation in Earth's interior. However, this simple ap-

proach has to be improved to account for the present-day mantle  $^{136}\text{Xe}_{\text{Pu}}/^{136}\text{Xe}_{\text{U}}$  ratio by introducing post-accretional (partial) degassing of the mantle towards an accumulating atmosphere as previously suggested [e.g., 9]. Taking this degassing into account we find that xenon accumulation in Earth already started 50–70 Ma after solar system formation, which was just after the extraction of the moon by a giant impact on proto-Earth [10]. This may indicate that the giant impact may have been the last total reset of the I-Pu-Xe system of an already completely (or nearly) assembled planet. On the other hand, this results is also consistent with scenarios, which suggest that a major part of Earth accreted rather rapidly just after formation of the moon.

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**THE PLANE TRUTH ABOUT PRIMORDIAL NOBLE GASES IN THE EARTH.** Grenville Turner, Peter Burnard and Darrell Harrison, Department of Earth Sciences, University of Manchester, Manchester M13 9PL, UK. (grenville.turner@man.ac.uk).

**Introduction:** In a recent report on the noble gas systematics of Popping Rock, Moreira et al. [1] used a novel and very powerful method of determining the isotopic and elemental composition of the upper mantle. The method makes use of isotopic and elemental correlations with neon, combined with the assumption that the  $^{20}\text{Ne}/^{22}\text{Ne}$  ratio of mantle neon is known and equal to the 'solar' value of around 13.8. The primordial component can be distinguished solely on the basis of the  $^{20}\text{Ne}/^{22}\text{Ne}$  ratio. Moreira et al. made use of the non-linear mixing diagram relating  $^{40}\text{Ar}/^{36}\text{Ar}$  and  $^{20}\text{Ne}/^{22}\text{Ne}$  to determine the  $^{40}\text{Ar}/^{36}\text{Ar}$  ratio of the MORB source region is less than 43,000. The importance of this conclusion lies in the relevance of the  $^{40}\text{Ar}/^{36}\text{Ar}$  ratio to models of transport from the lower to the upper mantle and from the upper mantle to the atmosphere.  $^{36}\text{Ar}$  in the upper mantle is assumed to originate in the lower mantle and the  $^{40}\text{Ar}/^{36}\text{Ar}$  ratio, is an important but poorly determined parameter in the steady state model of noble gas budgets.

**Neon - Argon Mixing:** In this abstract we draw attention to problems associated with the use of non-linear mixing diagrams to infer  $^{40}\text{Ar}/^{36}\text{Ar}$  and other ratios in the mantle. These problems are highlighted and partially overcome by the use of 3 dimensional linear mixing diagrams, e.g.  $^{20}\text{Ne}/^{22}\text{Ne}$  vs.  $^{40}\text{Ar}/^{22}\text{Ne}$  vs.  $^{36}\text{Ar}/^{22}\text{Ne}$ . On such a diagram it is possible to demonstrate the effects of elemental fractionation in addition to linear mixing. Indeed from the parameters of the mixing plane it is possible to establish which end member is fractionated. We conclude that  $^{40}\text{Ar}/^{22}\text{Ne}$  in Popping Rock is well established at  $400,000 \pm 36,000$ , but  $^{36}\text{Ar}/^{22}\text{Ne}$ , and by implication  $^{40}\text{Ar}/^{36}\text{Ar}$  in the upper mantle is not, owing to the presence of fractionated air. If we combine  $^{40}\text{Ar}/^{22}\text{Ne}$  in Popping Rock with the lowest primordial  $^{36}\text{Ar}/^{22}\text{Ne}$  ratio so far observed,  $\sim 6.5$  [2], we infer that  $^{40}\text{Ar}/^{36}\text{Ar}$  in the upper mantle could be as high as  $61,000 \pm 6,000$ .

**Neon - Xenon Mixing:** While  $^{40}\text{Ar}/^{36}\text{Ar}$  is important in fixing the parameters of the steady state model, this conclusion is unlikely to invalidate the model. In contrast, the isotopic and elemental ratios of xenon and neon are incompatible with the model. The problem is easily visualized using a plot of  $^{20}\text{Ne}/^{22}\text{Ne}$  vs.  $^{129}\text{Xe}/^{22}\text{Ne}$  vs.  $^{130}\text{Xe}/^{22}\text{Ne}$ . On such a figure MORB and hot spot compositions for not coplanar. This implies the presence of at least four components, one or more of which may be the result of elemental fractionation of one of the others.

Of the various possibilities, one which has some appeal, and is open to test, is that xenon analyzed in rocks from the upper mantle is the sum of; a  $^{129}\text{Xe}$  enriched component with a low Xe/Ne ratio from the lower mantle; subducted atmospheric xenon; atmospheric Xe and Ne present either as a contaminant or introduced by high level magma chamber processes; and component from the lower mantle which has been subjected in the upper mantle to elemental fractionation in which Xe/Ne is increased. Such an increase in Xe/Ne could arise if xenon were partitioned less efficiently than neon and the other noble gases during partial melting. A prediction of this model is that high  $^{129}\text{Xe}/^{130}\text{Xe}$  (or more easily  $^{129}\text{Xe}/^{132}\text{Xe}$ ) would be found in hot spot noble gases for which Xe/Ne was very low and  $^{20}\text{Ne}/^{22}\text{Ne}$  very high. Such analyses, with accurate determinations of  $^{129}\text{Xe}/^{132}\text{Xe}$  are rare or non-existent, but are beginning to appear in some of our recent analyses [2]. A simple way to search for the effect is on a plot of  $^{129}\text{Xe}/^{132}\text{Xe}$  vs.  $^{20}\text{Ne}/^{132}\text{Xe}$  vs.  $^{22}\text{Xe}/^{132}\text{Xe}$ .

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**FORMATION INTERVAL OF THE EARTH FROM IODINE-129/IODINE-127 AND PLUTONIUM-244/URANIUM-238 SYSTEMATICS AND MISSING XENON.** M. Ozima<sup>1</sup> and F. A. Podosek<sup>2</sup>, <sup>1</sup>Department of Earth and Planetary Physics, University of Tokyo, Tokyo 113, Japan (diamond@gpsun01.geoph.s.u-tokyo.ac.jp), <sup>2</sup>Department of Earth and Planetary Sciences, Washington University, St. Louis MO 63130, USA.

Although a quantitative accounting of the isotopic composition of Xe in the terrestrial atmosphere has remained elusive for generations, it is generally accepted that atmospheric Xe includes excess  $^{129}\text{Xe}$ , attributable to decay of  $^{129}\text{I}$ , and excesses of the heavy isotopes, attributable to actinide fission, most plausibly of  $^{244}\text{Pu}$ . It is not surprising that these components should be present in air, since the presence of  $^{129}\text{I}$  and  $^{244}\text{Pu}$  in the early solar system is well established. What is surprising is that abundance of the daughter Xe isotopes in air is so low. The straightforward interpretation is that the earth did not “form” (in the sense of isotopic closure of the I-Xe and Pu-Xe systems) until about  $10^8$  yr after meteorites [1]. This timescale is plausible in some respects but seems implausibly long in others (*e.g.*, some lunar samples are older [2] than the formation time of the earth thus inferred).

As a quantitative illustration, assume “coherent degassing” [3] such that the Xe daughters in air correspond to I and U (used as a proxy for Pu) in the crust. Taking radiogenic  $^{129}\text{Xe}$  to be 6% [4] and fission  $^{136}\text{Xe}$  to be 2.8% [5] of the atmospheric inventory, and crustal concentrations  $\text{I} = 1.55$  ppm [6] and  $\text{U} = 0.91$  ppm [7], we obtain closure values  $^{129}\text{I}/^{127}\text{I} = 10^{-6}$  and  $^{244}\text{Pu}/^{238}\text{U} = 0.0024$ . These are reasonably consistent with nominal meteoritic values ( $10^{-4}$  and 0.007, respectively) with allowance for about 105 Ma of decay before closure.

As one way around the problem of too long a formation interval for the earth we suggest invocation of another traditional “problem”, that of the so-called “missing Xe”. The abundance of Xe in air is at least an order of magnitude lower than analogy with “planetary” gases in meteorites

would suggest, whence it is hypothesized that the earth had or still has the missing Xe, but not in the atmosphere. Attention to this problem has waned as the missing Xe was sought but not found in proposed surficial reservoirs and as the meteorite analogy has weakened with recognition that some or perhaps even most of the “planetary” gases are actually presolar. Nevertheless, we argue that there still is a missing-Xe problem. Xe/Kr in air is only about half the solar value, and by whatever mechanism in whatever venue, it is plausible that Xe/Kr in the earth should be at least as high, and probably considerably higher, than the solar value.

Qualitatively, if originally trapped Xe is missing then some of the daughter  $^{129}\text{Xe}$  and  $^{136}\text{Xe}$  are likely also missing, so that the original amounts of  $^{129}\text{I}$  and  $^{244}\text{Pu}$  inferred from present atmospheric Xe are too low. The effect depends not only on how much Xe is missing but also on when it was lost: If too early the daughter isotopes are not lost, and if too late the inferred abundance of  $^{244}\text{Pu}$  is too high. As a specific quantitative example, if present atmospheric Xe is only 10% of the original inventory, and the loss or sequestration of the other 90% occurred some 80 Ma after formation, the initial abundances of  $^{129}\text{I}$  and  $^{244}\text{Pu}$  are consistent with meteorite values after a formation interval reduced to about 55 Ma.

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**ACTIVE CAPTURE OF VOLATILES: IMPLICATIONS FOR PLANETARY AND ATMOSPHERIC XENON.** C. M. Hohenberg<sup>1</sup>, N. Thonnard<sup>2</sup>, K. Kehm<sup>1</sup>, A. P. Meshik<sup>1</sup>, A. Berryhill<sup>2</sup>, and A. Glenn<sup>2</sup>, <sup>1</sup>Washington University, Department of Physics, St. Louis MO 63130, USA <sup>2</sup>Institute for Rare Isotope Measurements, Oak Ridge TN 67932, USA (cmh@wuphys.wustl.edu).

**Introduction:** It is difficult to understand how two reservoirs of noble gases, solar and planetary, can exist in the solar system. Either there must have been some unknown mechanism for introducing and maintaining separate components in the primitive solar nebula, or these reservoirs must be related by known physical processes such as mass fractionation and (well understood) radioactive decay.

What is phase Q and how were heavy planetary noble gases incorporated into it? A variety of different mechanisms for incorporation into solids and mass fractionation may have been at work, and the light noble gases are different from the heavy. It has been suggested that one mechanism important for heavy noble gases is low-energy ion implantation. This process has been modeled using cathodless glow discharge [1] and a modified Bayard-Alpert ion gauge [2]. Both of these experiments yield Xe mass fractionation of 1% or less, whereas planetary (and atmospheric Xe) differs from solar by about 3.5% per amu (2-3% for atmospheric). Although recently improved and modified [3], such experiments still produce fractionations of only 1%, not enough to account for Q (planetary) Xe, if derived from solar. We have undertaken a different implantation experiment, one initially designed for the active capture of cometary volatiles [4]. Results presented here are a by-product of that project.

**Experimental:** The ion source, taken from a quadrupole mass spectrometer, is capable of providing a more stable and controlled ion beam than the Bayard-Alpert geometry used previously. The most critical difference from previous experiments, however, is that low-energy (0.15 eV/amu) implantation is done simultaneously with the deposition of a low-Z metal film onto a sapphire substrate, perhaps a more realistic simulation of Xe capture onto surfaces in the early solar nebula.

**Results:** 20 eV Xe ions, implanted simultaneously with deposit of Al or Mg films, was released by laser extraction [5] and analyzed by a magnetic sector mass-spectrometer [6]. As was reported earlier, the capture efficiency was measured to be about 1% [4], with an accompanying isotopic mass fractionation of 3.5% per amu in favor of heavy isotopes. The capture efficiency for noble gases lighter than Kr is essentially zero [4]. The magnitude and sense of Xe mass fractionation in this process are equal to that observed for

planetary Xe if it were derived from a primitive nebula component of solar composition. Atmospheric Xe could be derived from planetary, showing similar fractionation, but its isotopic structure demonstrates effects such as the addition of CFF [7] and radiogenic components.

**Conclusions:** What is phase Q and how is Q Xe acquired? Its chemical/physical properties suggest that Q is a 2-D matrix, likely a carbonaceous surface layer. Light noble gases are not associated with Q, or at least are present in a much lower abundance than the heavy noble gases. Low-energy capture simultaneously with film formation (by solar hydrogen reduction of CO?) may result in a huge Xe capacity and low concentrations of light noble gases.

Can planetary Xe be derived from solar Xe by active capture, low energy implantation with simultaneous deposition (accretion) of a low-Z material? Is this phase Q?

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In January of this year, Dr. Daniel Goldin ordered the release of mass spectrometer data from the 1995 entry of the Galileo probe into Jupiter [1]. The presence of Xe-X in Jupiter gives an positive answer to the last of three proposed tests for diffusive enrichment of lighter nuclei at the solar surface [2]. Xe-X is the isotopically strange X that has been found to be tightly coupled with primordial He in meteorites [3]. Xe in Jupiter is closer to Xe-X than to solar wind (SW) Xe. The latter is a mass fractionated form of terrestrial Xe (Xe-T) with lighter isotopes selectively enriched by about 4% per amu [4] from diffusive mass fractionation [5].

The first and second proposed tests of intra-solar diffusion were answered affirmatively by a) mass fractionation across SW Mg isotopes that parallel those seen across rare gas isotopes [6], and b) the low flux of solar neutrinos observed with the Kamio-kande and the  $^{71}\text{Ga}$  detectors [7].

The finding of Xe-X in the He-rich atmosphere of Jupiter has two important implications: (1) The primordial linkage [3] of Xe-X with He spanned planetary distances in the proto-solar nebula, as has also been concluded for the primordial linkage of Xe-T with FeS [8]. (2) The proto-solar nebula was chemically and isotopically heterogeneous, as expected of supernova debris [3]. Thus, Jupiter formed out of material containing Xe-X and much He, while the Sun and the terrestrial planets formed in a central region that included Xe-T and abundant Fe, S.

The presence of mass fractionated Xe-T in the solar wind suggests that the H,He-rich solar surface may conceal an Fe,S-rich interior, much as the red peel of an apple conceals an interior of different color. Although H and He are abundant elements in the photosphere, major elements in the bulk Sun are (in decreasing order): Fe, Ni, O, Si, S, and Mg [2] after correcting for the mass fractionation effects seen across isotopes in the solar wind (see Fig. 1). This shows that the Sun and the four terrestrial planets consist of the same elements.

High energy events, such as flares, disrupt intra-solar diffusion [6]. Hence, solar energetic particles are less enriched in light isotopes than are elements in the quiet solar wind [6]. Since the average weight of particles in the sun is closer to 56 than to 1 amu, the average temperature must be higher to explain the Sun's overall density. Thus, fusion reactions may not be limited to the Sun's inner core. The inverse

correlation between the solar neutrino flux and sun spot number [7] suggests that solar flares also disrupt nuclear fusion reactions outside the Sun's core.

## Composition of the Sun after correction for diffusion

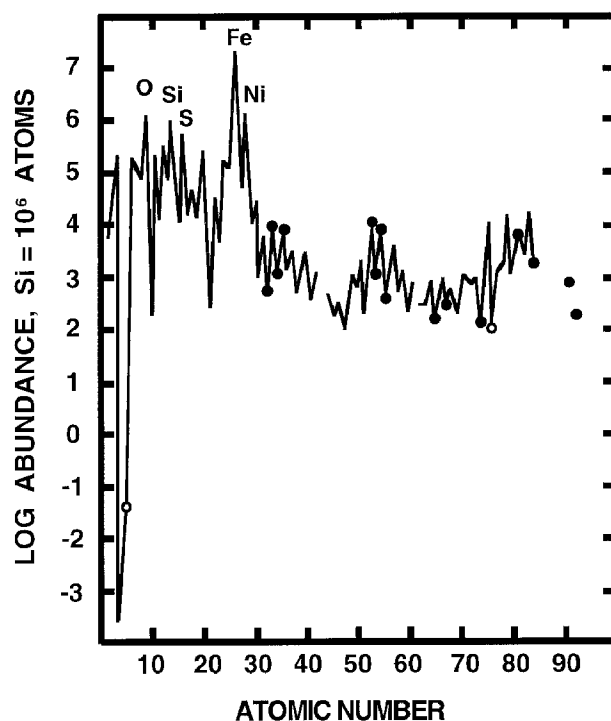


Fig. 1

**Acknowledgments:** This paper is dedicated to my students and colleagues.

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**THE “UREY HYPOTHESIS” REVISITED: MOLECULAR GENETICS AND CONTEMPORARY CHRONOLOGIES.** L. C. Hill, Jr., Natural Science Department, Broward Community College, Davie FL 33314, USA.

The “Urey Hypothesis” [1] linked the extremely reducing intracellular chemistry of terrestrial life to an early epoch of terrestrial history when the Earth’s atmosphere would have been chemically similar to the cosmically normal jovian planets. A central assumption of the hypothesis was that biological evidence can be used to deduce conditions about the very early Earth (*i.e.*, the Hadean Earth). However, during the past few decades this assumption has often been rejected because other evidence (volatile inventories [2]; loss of noble gases [3]) suggested that there was no relevant evidence of an early H-rich era within the datable geological record. More recent efforts have suggested that the history of the Hadean earth was punctuated by extremely energetic, even catastrophic, impacts [4,5] and thus have seemed to further consign the Urey Hypothesis to the category of an interesting irrelevancy. It is to be noted, however, that the rejection of the Urey Hypothesis is not normally based upon an analysis of the biological record *per se*, but upon the belief that the geological, meteoritic, lunar and planetary records combined provide an apparently consistent interpretation of an early Hadean eon *sans* life and *sans* H.

The recent discovery [6] of 3.85+ Ga BP life in the Issua sediments has, however, reopened this issue. There is not, in fact, any unambiguous evidence that the datable geological record actually precedes the origin or emergence of terrestrial life. Indeed, recent advances in molecular genetics have demonstrated that the last common ancestors (LCA) of all terrestrial life were extremely anaerobic, probably thermophilic and/or halophilic microbial entities environmentally tolerant of commonly conceived Hadean conditions [7]. Furthermore, the detailed parsing of enzymatic molecular phylogenies [8–10], particularly those of N fixation, reveal hints of even earlier ancestors, the “progenotes”. It is argued in this paper that the subordinated genetic linkage of all nitrogenase ac-

tivity to hydrogenase activity (the reverse linkage is not found) is in fact a record of the passage of all life through an evolutionary bottleneck which occurred when the earliest identifiable “home”, an H-rich, ammoniated “pool, vent, lake, ocean or world” was gradually transformed into the still anaerobic, but no longer H-rich Earth of the late Hadean and early Archean eons. This very early progenotic event is currently undated on an absolute time scale, but a plausible and very broad relative phylogenetic chronology suggests that these enzymes and their genes are molecular fossils with roots which reach deep back into the Hadean eon. It is further argued that recent work [11–13] makes it unprofitable for planetary scientists to subsume the entire 700 Ma history of the Hadean eon under the rubric of a few geologically instantaneous sterilizing and/or Earth-melting impacts. Instead, it is suggested that biological evidence may provide important and otherwise unavailable indicators of widespread Hadean conditions.

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